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Quantifying the impact of cascading use: A comparative integrated assessment of the European pine chemicals industry

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ABSTRACT

In recent years, following the amendment to the European renewable energy directive (RED), there is an increasing interest to exploit Crude Tall Oil (CTO) for energetic purposes. This study conducted an integrated assessment to quantify the environmental, economic and social impact of these two competing material and energetic routes that consume CTO as a feedstock. The integrated assessment follows a cradle-to-grave approach to compare the impact on climate change from the production of bio-chemicals to that generated from the production of renewable diesel from CTO. In addition, the economic and social impact assessment estimates the total economic added value as well as the total number of direct, indirect and induced jobs generated by the two respective routes utilising CTO. The environmental assessment showed that the application of CTO for bio-chemicals has 23% lower greenhouse gas emissions than its application for renewable diesel. The economic assessment showed that the European pine chemicals industry generated at least 4 times higher added value than that generated from renewable diesel. Finally, when analysing the social impact, the utilisation of 650,000 of CTO to produce bio-chemicals generated around 9100 jobs. On the other hand, the renewable diesel production route was estimated to generate only 400 jobs. Therefore, the integrated assessment concludes that, diverting and utilising CTO to produce biofuels does not present a sustainable case when compared to its established use in the production of bio-chemicals.

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1. Introduction

Pine chemicals can be categorised as one of the earliest segments of the bio-based chemical industry, where tapping pine trees for rosin and using primitive forms of pine tars and pitch date back to ancient times (Panda, 2013). Pine chemicals today are largely produced by upgrading co-products of the Kraft pulping process into a multitude of consumer products (Coll et al., 2001; Stubba et al., 2015). With rising demand for wood in the European Union (O'Brien and Bringezu, 2018), primarily driven by energetic use to meet renewable energy targets (Mola-Yudego et al., 2017), there is a growing concern to address deficit in wood supply (Alberdi et al., 2016) through the principle of cascading use (CU) (Sirkin and Houten, 1994; Fraanje, 1997), addressing the resource efficient use of biomass resources. The underlying principle argues for the sequential and resource efficient utilisation of biomass, biomass residues and by-products which are refined into different product classes of higher value (Mantau, 2015). In short, material use of biomass should take precedence over energetic use (Olsson et al., 2016).

One example for the cascading use principle and therewith an approach to circular economy (Mair and Stern, 2017) can be found in the paper and pulp industry. Pine chemicals are largely produced from crude tall oil (CTO), a co-product of the Kraft pulping process (Panda, 2013). CTO is a constrained raw material with global annual availability of around 2 million tonnes and an EU wide availability of approximately 650,000 tonnes. Instead of direct incineration, the European CTO industry has for many decades, processed this limited resource in technically complex biorefineries using the cascading principle (see Fig. 1), to produce bio-based intermediates that are building blocks for a number of everyday end-use products.

However, in recent years, following the classification of CTO as a 'process residue' under Article 2 of the current Renewable Energy Directive (Directive, 2009/28/EC) (The European Parliament and the Council, 2015), there is an increased exploitation of this raw material for its use in biofuels. In order to achieve their respective national renewable energy targets, few EU member states have

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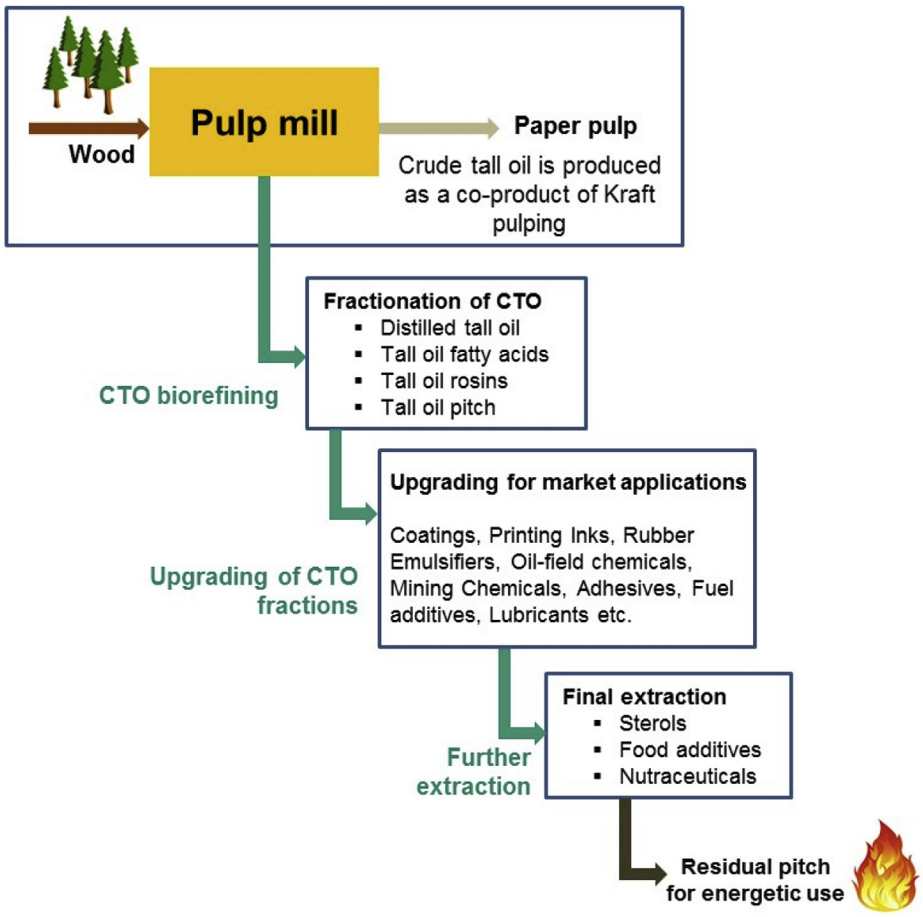

Fig. 1. Cascading use of CTO in pine chemicals industry.

introduced practices (the so-called 'multiple counting') to incentivise the utilisation of CTO for energetic use rather than creating bio-based products of higher value (Carus et al., 2014). Consequently, there is now an additional demand for CTO that is already fully utilised by the European pine chemical industry to produce bio-based chemicals. As a co-product of the paper and pulp industry, CTO availability is reliant on the Kraft pulping process, where its yield is approximately 35–40 kg per tonne of pulp processed. This indicates that there is a finite amount of CTO on the world's market and any increase in demand for CTO does not lead to an increase in its supply.

Therefore, the goal of the study is to conduct an integrated sustainability assessment by analysing the total value generated from the resource utilisation of CTO in two competing applications in Europe (see Table 1).

2. Research methodology

To analyse the presented scenarios, the integrated sustainability assessment takes a three-fold approach to quantify the economic value, environmental impact and social impact of the present day European pine chemicals industry against the potential impacts that could be generated from emerging biofuels application. Therefore, the analysis comprises the following:

a) Determining the impact on global warming including the substitution effects for both scenarios
b) Estimating the economic added value measured in terms of total revenues generated in both scenarios
c) Finally, the determination of social impact with specific focus on the total number of jobs generated (direct jobs, indirect jobs and induced jobs)

In both scenarios, the impacts were estimated for the base year 2016. For the products in Scenario 1, the adjusted prices from the Eurostat producer price index (PPI) for the manufacture of chemicals and chemical products were taken, while for Scenario 2, the EU commodity prices for fuels were used. A comprehensive methodology is outlined in respective sections (see section 3, and section 4).

Table 1
List of scenarios assessed in this study.

Scenario	Description
1	Conversion of CTO fractions to a range of bio-based chemicals
2	Conversion of CTO to renewable diesel

2.1. CTO composition

Crude tall oil like any other bio-based raw material has varying composition based on several factors such as the type of pine trees, geographical location etc. Due to complex nature of the feedstock and the lack of a more widely accepted data on composition, the scientific data published by VTT (Anthonykutty et al., 2013) for the hydroprocessed tall oil distillate was taken. The reason for using

depitched fraction as a basis was to make a fair and balanced analysis of the environmental impact for Scenario 1 and 2. Hence, it was assumed in both scenarios that the tall oil pitch (TOP) will be sold "as is" and not be processed further. Therefore, any value generated from TOP in either scenarios is simply equated to the price of the lower heating value (LHV) of pitch fuel.

The composition of the tall oil distillate (fraction excluding the TOP) used as a reference feed for Scenario 2 is shown in Table 2. The typical composition of EU based tall oil fractions: tall oil fatty acids (TOFA), tall oil rosins (TOR), distilled tall oil (DTO) and TOP is shown in Fig. 2.

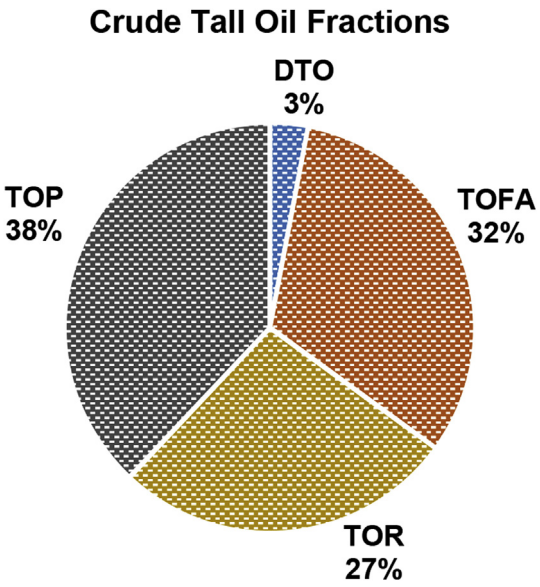

Fig. 2. Crude tall oil intermediated fraction.

3. Environmental assessment

The life cycle assessment detailed in this paper includes a definition of the goal and scope (section 3.1), a life cycle inventory analysis (section 3.3), an impact assessment and the interpretation of results (section 3.4). The LCA was conducted considering the ISO 14040/44 standards (ISO, 2006) using the commercial software GaBi ts 7.3.3.

3.1. Goal and scope

The goal of the LCA was to compare the potential contribution of two dictinct CTO applications to the climate change. Table 1 shows the two investigated scenarios. The relative contributions to greenhouse gas (GHG) emissions as a result of using CTO to produce renewable diesel (Scenario 2) against its current use in the production of bio-based chemicals (Scenario 1) was assessed. The balance of GHG emissions associated with each case also includes the saved (substituted) greenhouse gas emissions from the production of existing products in the European market that can be replaced by CTO-derived products, and the saved GHG from the production and combustion of substituted fossil fuels. The study follows an attributional approach. The geographical scope of the study concerns Europe and is limited to the volumes of pine chemicals recovered in the Kraft pulping process. The study neglects any imported volumes of CTO and merely considers the amount of 650,000 tones available within the European Union (EU).

3.1.1. Functional unit

The functional unit considered in both scenarios was the use of 1 Mg of CTO. The selection of this functional unit allows for comparison of different end-use applications of CTO. In both scenarios, the TOP fraction, which represents about 38% in mass, was modelled to be seperated from the remaining CTO fraction. The seperated TOP was assumed to be consumed as fuel for in-situ process heat generation in both scenarios.

3.1.2. Choice of life cycle impact indicator

The global warming impact (GWI) was considered as the sole environmental impact indicator in this study (IPCC, 2007a). Greenhouse gas (GHG) emissions originating only from non-renewable sources are taken into consideration, as this is a common practice in LCA studies (Levasseur, 2015). The result of this impact indicator yields an estimation for the emissions of GHG (e.g., carbon dioxide, nitrous oxide, methane, halocarbons) that can occur during any of the investigated processes included within the system boundaries. This indicator was chosen because it refelects the impacts from steam and electricity generation which are the main resources used to process CTO in both scenarios. In addition, hydrogen produced from steam reforming is used to convert CTO to a renewable diesel in Scenario 2.

Although they are out of the scope of the present study, it is to be noted that environmental impacts other than the GHG emission may occur. Burning fuels for energy generation is also linked to emission of precursors to tropospheric ozone (e.g., nitrogen oxides and volatile organic compounds) and toxic compounds (e.g., benzene, toluene, xylenes, and nitrogen dioxide) (Monks et al., 2015). Furthermore, some CTO-derived chemicals may have toxic effects during the use stage and volatile organic compounds are likely to originate from solvents added to produce the final chemical products. However, a number of CTO chemical products - such as resin acids, esters with pentaerythritol and alkyd resins - are in general not classified as hazardous (Norlin, 2000). Likewise, the use of renewable diesel in internal combustion engines may result in contributions to acidification and eutrophication (Nanaki and Koroneos, 2012).

Table 2
Detailed composition of Tall Oil Distillate.

Elemental composition	**Fraction**
Carbon	77,4
Hydrogen	11,1
Sulphur	0,05
Oxygen	11,5
Acids composition	**Fraction**
Total free fatty acids (FFA)	71,3
Total resin acids	23

3.1.3. Handling of multifunctionality

In order to account for the substitution of fossil-based products by CTO products, corresponding credits were given. In detail, the balance of GHG emissions calculated for Scenario 1 also includes an estimation of the amount of saved emissions from: (a) the production of fossil-based existing products in the European market that could be replaced by CTO-derived chemicals, and (b) from the production and use of fossil fuels that could be replaced by CTO-derived fuels. In addition, in the case of TOP, credits based on heating values were given for substituting heavy oil as fuel for process heat generation in both scenarios.

In order to allocate environmental burdens to CTO, mass allocation was used to distribute burdens between black liquor solids (BLS), wood fibres, CTO and crude sulfate turpentine (CST) resulting from the Kraft pulping process and its linked prechains (Cashman

et al., 2015).

3.2. Systems under study and life cycle inventory analysis

Both scenarios begin with the production of CTO from pine wood, starting from: (a) the cultivation and harvesting of pine trees; (b) kraft pulping process, where CTO precursors are hydrolysed to soluble sodium soap in the reaction medium; and (c) the separation of the soap from black liquor and its conversion to free fatty and resin acids by reaction with sulphuric acid (acidulation) (Norlin, 2000). The data on the emission of greenhouse gases released during the production of CTO from pine wood was obtained from the study by Cashman et al., (2015).

3.2.1. Conversion of crude tall oil for chemical applications

The system boundaries for the analysis of the use of CTO to produce primary tall oil fractions and bio-chemicals thereof (Scenario 1), is shown in Fig. 3.

CTO is first dehydrated in an evaporator under vacuum (3–6 kPa, up to 200 °C), where water and other compounds known as heads (mixed neutral compounds and short chain fatty acids) as well as turpentine are separted (Norlin, 2000). Following this, the resulting CTO fraction is then subjected to fractional distillation under vacuum (0.13–1.3 kPa, 270–330 °C). Wherein, the TOP is seperated in a first fractionating tower, and in a second column DTO, TOFA and TOR are separated (Norlin, 2000). It was assumed that the CTO-based chemicals except fuel additives, oil field and mining chemicals are incinerated after their use stage in a municipal solid waste incinerator. Credits were given for thereby generated heat and electricity.

The inventoried data for Scenario 1 is shown in Table 3. The total energy demand to distill CTO to produce tall oil fractions were taken from Cashman et al. (2015). It was assumed that all CTO is converted to tall oil fractions without generating waste, with a conversion rate of 100%.

3.2.2. Use of CTO to produce renewable diesel

The flow diagram and the system boundaries for the analysis of the use of CTO in the production of renewable diesel (Scenario 2), is show in Fig. 4. Firstly, CTO undergoes a distillation step in which TOP is separated. Then the depitched crude tall oil is hydrotreated (hydrodeoxygenated). At temperatures around 325 °C–375 °C on a sulfided hydrotreating NiMo catalyst, hydrogenation of double bonds and deoxygenation (removal of oxygen) of fatty and resin acids occur (Anthonykutty et al., 2013; Mikulec et al., 2012). The conversion of fatty and resin acids in a so-called hydroprocessing step is believed to occur mainly through hydrodecarbonylation, hydrodeoxygenation and decarboxylation reactions (Anthonykutty et al. 2013, 2015b).

$$RCOOH + H_2 \rightarrow RH + CO + H_2O \quad (1)$$

$$RCOOH + 3\,H_2 \rightarrow RCH_3 + 2\,H_2O \quad (2)$$

$$RCOOH \rightarrow RH + CO_2 \quad (3)$$

At temperatures above 375 °C, hydrocarbons without oxygen (mainly composed of alkanes derived from the deoxygenation of fatty acids, but also nonaromatic cyclic compounds obtained from the deoxygenation of resin acids) are cracked and isomerised to yield a product mix that is lighter, branched and dispalys a lower melting point (Anthonykutty et al., 2013). Cracking may produce compounds that are too short-chained to be efficiently used in diesel. This fraction of lighter molecules will mainly produce naphtha (lighter alkanes) during subsequent fractionation.

Following hydroprocessing, the gas-liquid reaction mixture is directed to a separator. Unreacted hydrogen is recycled back to the reactor, where make-up hydrogen is introduced (Stumborg et al., 1996). Finally, after separation of the water phase, the organic phase is distilled to yield renewable diesel and naphtha. A simplified overall reaction is:

$$CTO + H_2 \rightarrow Renewable\ diesel + gases\ (CO_2,\ CO) + H_2O + naphtha \quad (4)$$

The datasets used for the Scenario 2 are shown in Table 4. The mass ratio of renewable diesel to depitched CTO was calculated to be 0.86. The stoichiometric amount of hydrogen consumed for complete deoxygenation and hydrogenation was considered to be 40 kg H_2/t depitched CTO (Anthonykutty et al., 2013).

3.2.3. Choice of reference system

System expansion was applied in both scenarios to account for the fact that CTO is processed into multiple products.

3.2.3.1. Replacement of fossil-based chemical products. Because of their fatty and resin acids content, TOR, DTO and TOFA fractions are used to produce a wide range of chemical products (Norlin, 2000). Table 5 shows the applications and main substituted products from each CTO fraction, as well as the amount of GHG emissions associated with the production of the substituted products. For these tall oil fractions, it was assumed that 1 mass unit of each tall oil application replaces 1 mass unit of alternative product (Cashman et al., 2015).

The amount of GHG emissions associated with the production of alternative products is 1523 kg CO_2 eq./t CTO (see Table 6).

As shown in Table 8, TOP may be a substitute for heavy oil. The specific greenhouse gas emissions for heavy fuel oil production and combustion were calculated based on the lower heating values (LHV). The following LHV values were used in this study: 40.6 MJ/kg for TOP (Tanaka et al., 1980), 40 MJ/kg for heavy oil (European Parliament and Council of the European Union, 2006), 44 MJ/kg for renewable diesel (European Parliament and Council of the European Union, 2009; Neste Oil, 2012), and 43 MJ/kg for fossil diesel (European Parliament and Council of the European Union, 2009).

The amount of greenhouse gas emissions related to the production and combustion of heavy oil is 1338 kg CO_2 eq./t CTO (see Table 6).

At the end of their life-time, waste chemicals must be managed. Despite the fact that a detailed analysis of their management is out of the scope of the present study, it was assumed that a common treatment for most waste containing CTO-derived chemicals is incinerated with energy recovery. Those waste fractions that may follow this route are waste derived from the manufacture and use of products such as coatings, adhesives and inks, rubber, lubricants, as well as oil waste and oil emulsions (European Commission and Joint Research Centre, 2009). Table 7 shows the estimated mass and energy flows associated with the incineration of waste chemicals, and the emission factors used to calculate the balance of greenhouse gas emissions. As background data, an average European waste-to-energy plant with an average efficiency of the steam production of about 81.9% was assumed. About 26% of the energy is converted into electricity and 74% remains thermal energy, which replace average European electricity grid mix and thermal energy from natural gas. For the fed electricity 7% grid losses are taken into account. A negative flow of greenhouse gas emissions indicates the saved emissions.

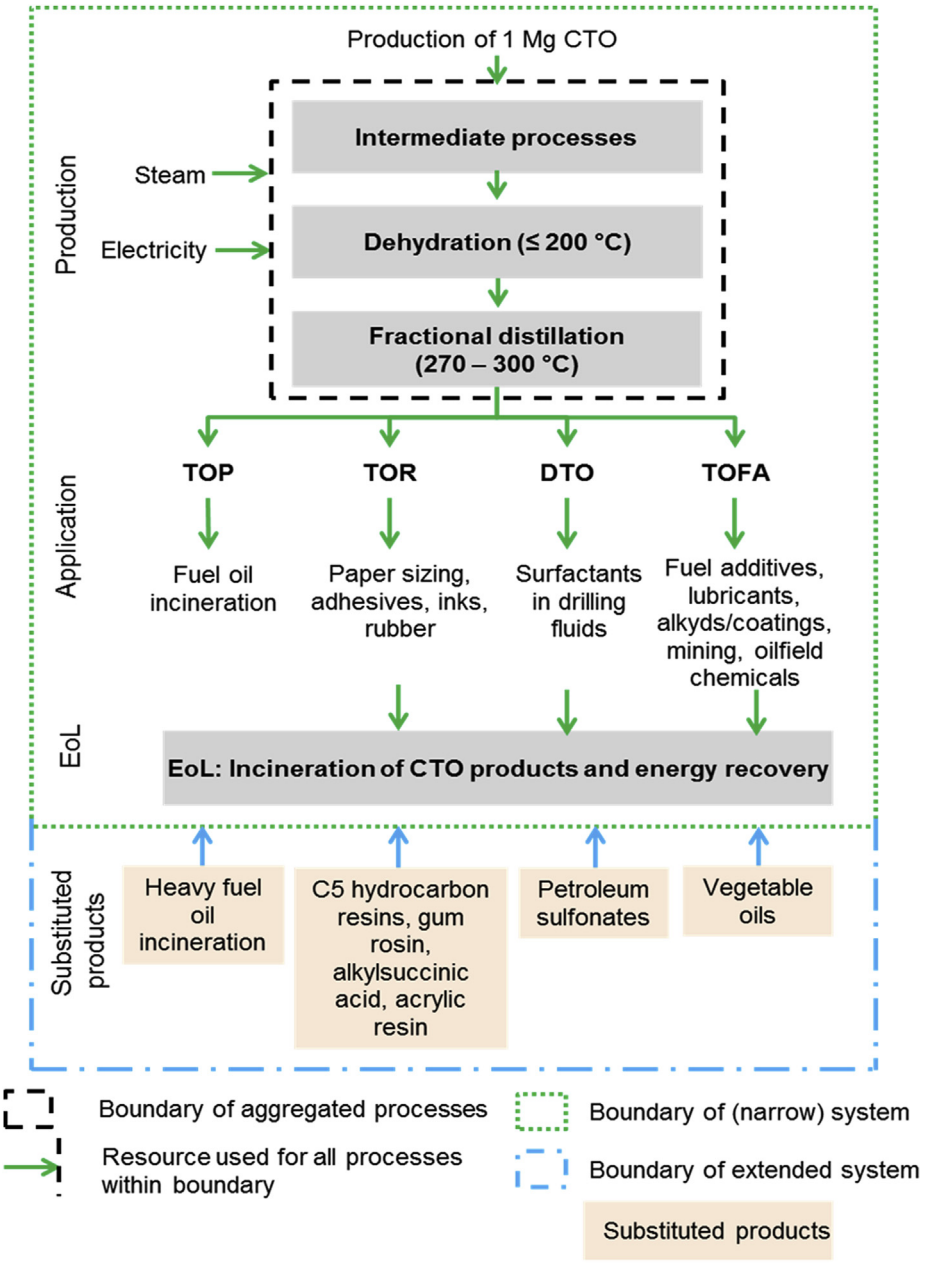

Fig. 3. System boundary for Scenario 1 - CTO to bio-chemicals.

Table 3
Mass and energy flows associated with the distillation of 1 Mg CTO to 1 Mg CTO fractions for bio-chemicals, and their respective GHG emissions.

Mass or energy flow	Amount	Data source	Specific GHG emissions	Source: specific GHG emissions
Input flows				
CTO	1 Mg	Estimated data	678 kg CO_2 eq./Mg CTO	Cashman et al. (2015)
Electricity	173 kWh	Cashman et al. (2015)	0.238 kg CO_2 eq./kWh electricity	GaBi dataset: "RER: Power grid mix (NORDEL)"
Heat (steam)	2230 MJ (back calculated based on average end-use steam load efficiency of 68%)	3280 MJ/Mg CTO (Cashman et al., 2015)	0.099 kg CO_2 eq./MJ steam	GaBi dataset: "EU 27 Process steam from heavy oil, 90% efficiency"
Output flows				
CTO fractions for bio-chemicals	630 kg	Estimated data		
TOP	370 kg	Estimated data		

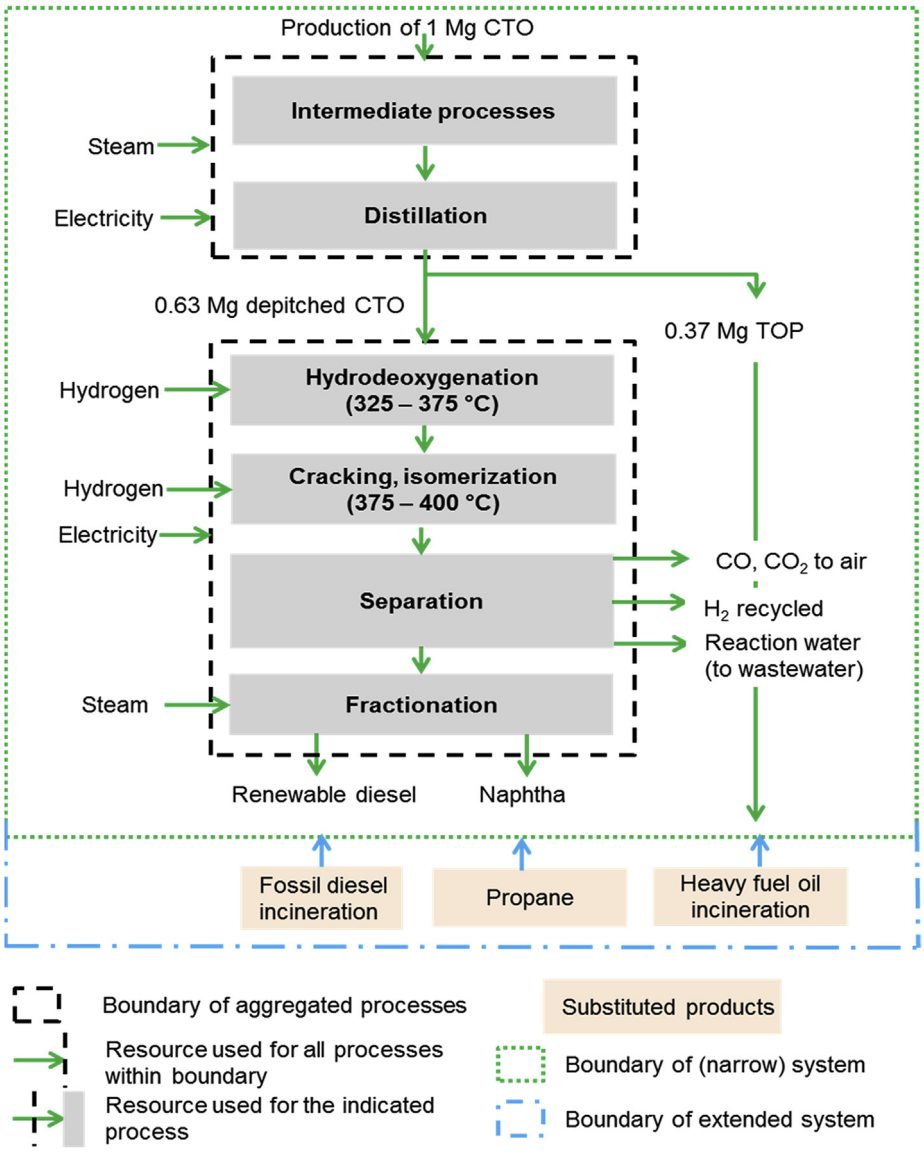

Fig. 4. System boundary for Scenario 2 - CTO to renewable diesel.

3.2.3.2. Replacement of fossil diesel. The renewable diesel produced from CTO may substitute fossil diesel. Table 8 indicates the substituted fossil fuels for each CTO-derived fuel considered in this study, as well as the emission factors applied to estimate the corresponding saved emissions. The LHV values mentioned earlier were used in the calculations.

Table 4
Mass and energy flows associated with the hydroprocessing 1 Mg CTO to 0.54 Mg renewable diesel, and specific greenhouse gas emissions.

Mass or energy flow	Amount	Data	Data source	Specific GHG emissions	Source: specific GHG emissions
Input flows					
CTO	1 Mg			678 kg CO_2 eq./t CTO	Cashman et al. (2015)
Electricity	57 kWh	106 kWh/Mg renewable diesel	(Neste Oil, 2012, 2014)	0.238 kg CO_2 eq./kWh electricity	GaBi dataset: "RER: Power grid mix (NORDEL)"
Heat (steam)	2160 MJ	600 kWh steam/Mg CTO	Stigsson et al. (2014)	0.099 kg CO_2 eq./MJ steam	GaBi dataset: "EU-27 Process steam from heavy oil, 90% efficiency"
Hydrogen	27 kg	Stoichiometric mass H_2: 40 kg H_2/Mg DTO; make-up H_2: 7.89%	(Anthonykutty et al. 2015a, 2015b; Neste Oil, 2012)	11.50 kg CO_2 eq./kg H_2	GaBi dataset: "EU-27: H_2.Steam reforming- natural gas"
Output flows					
Renewable diesel	0.54 Mg	Mass ratio renewable diesel/DTO: 0.86	Anthonykutty et al. (2013)		
TOP	0.37 Mg		Estimated data		
CO_2, CO, H_2O, naphtha	115 kg	Calculated mass balance (without make-up H_2)			

Table 5
Crude tall oil fractions, their applications, main substituted products in the European market, and avoided greenhouse gas emissions.

CTO fraction	Amount (kg product/Mg CTO)	Application	Substituted products	GHG emission factors (kg CO_2-eq./Mg sub. prod.)	Source: GHG emission factor
TOR	270	Paper size	Gum rosin, alkylsuccinic acid	2410	Franklin Associates (2013)
		Adhesives	C5 hydrocarbon resins	2940	Franklin Associates (2013)
		Inks	Acrylic resin	4538	ecoinvent dataset: "GLO: market for acrylic binder, without water, in 34% solution state"
		Rubber	C5 hydrocarbon resins	2940	Franklin Associates (2013)
		Others	No data available	3207 (average)	
TOFA	320	Fuel additives Lubricants Alkyds/Coatings Mining Oilfield chemicals	Vegetable oils (soybean oil)	1830	ecoinvent dataset: "RER: soya oil, at plant"
		Others	No data available	1830	
DTO	40	Surfactants in drilling fluids	Petroleum sulfonates	1903	Defever and Polastro (2010)

Table 6
Amount of greenhouse gas emissions attributed to the production of substituted chemicals and heavy oil.

Substituted products by CTO fractions	Specific GHG emissions (kg CO_2 eq./t CTO)
Alternatives to CTO-derived chemicals	1523
Heavy fuel oil	1338

Table 7
Mass and energy flows for incinerating 492 kg of waste chemicals with energy recovery, and greenhouse gas emissions related to non-renewable sources.

Mass or energy flow	Amount	Specific GHG emissions from non-renewable sources	References and background data
Input flows			
Waste chemicals	492 kg		
Electricity	30 MJ	40.2 kg CO_2 eq./Mg waste	ELCD-dataset: EU-28: Waste incineration of wood products
Heat	108 MJ		
Output flows			
Electricity	953 MJ	- 0.162 kg CO_2 eq./MJ electricity from grid	GaBi dataset "EU-25: Electricity grid mix (for credit)"
Heat	2926 MJ	- 0.0687 kg CO_2 eq./MJ heat from natural gas	GaBi dataset: "EU-27: Thermal energy from natural gas (for credit)"

Table 8
CTO-derived fuels, main substituted products in the European market, and specific greenhouse gas emissions.

CTO fraction	Amount (kg product/Mg CTO)	Application	Substituted product	GHG emission factor (g CO_2 eq./MJ sub. prod.)	Source: GHG emission factor
TOP	370	Fuel	Heavy oil	89.1	GaBi dataset: "EU 27 process steam from heavy oil, 90% efficiency"
Renewable diesel	542	Fuel	Fossil diesel	83.8	European Parliament and Council of the European Union (2009)

3.3. Results and discussion – environmental assessment

In this section the results of the environmental impact assessment for the chosen impact indicator global warming impact is discussed in detail.

3.3.1. Use of crude tall oil to produce tall oil fractions for bio-chemicals

The distribution of GHG emissions associated with the production and distillation of CTO to tall oil fractions for bio-chemicals is shown in Fig. 5 (see also Table 9).

The total greenhouse gas emissions for Scenario 1 is 940 kg CO_2-eq./Mg CTO, with CTO production (72% of the total emissions) and steam production for CTO distillation (24%) being the two main contributing processes. However, when the amount of TOP produced (370 kg/Mg CTO) from CTO fractionation is substitute for the required energy demand needed for distillation, the total emissions is reduced to 719 kg CO_2-eq./Mg CTO.

Fig. 6 shows the balance of GHG emissions considering the expanded system. Combustion of TOP instead of heavy oil may replace a total amount of 1338 kg CO_2-eq./Mg CTO (see Table 6). Use of TOR, TOFA and DTO for the production of chemicals replaces 1523 kg CO_2 eq./Mg CTO (see Table 6). The incineration of waste chemicals with energy recovery replaces 335 kg CO_2-eq./Mg CTO. The net balance results in an amount of saved GHG emissions of 2256 kg CO_2-eq./Mg CTO processed to bio-chemicals.

3.3.2. Use of crude tall oil to produce renewable diesel

Fig. 7 (see also Table 9) summarises the distribution of GHG emissions associated with the production of renewable diesel from CTO. The total amount of emissions for Scenario 2 is 1218 kg CO_2-eq./Mg CTO. Wherein, the emissions associated with CTO

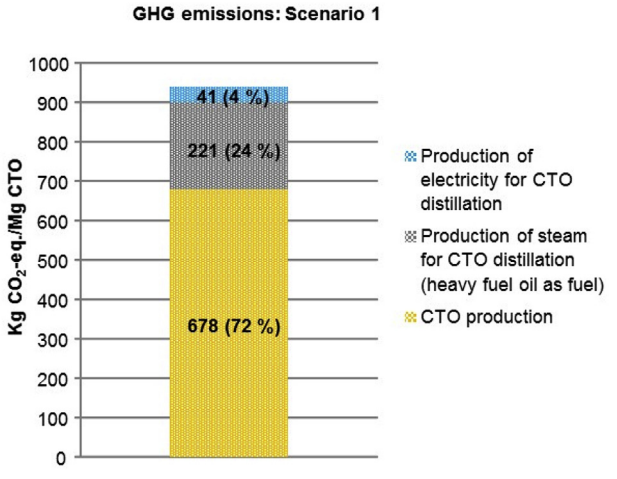

Fig. 5. Balance of GHG emissions assigned to CTO production and processing to biochemicals.

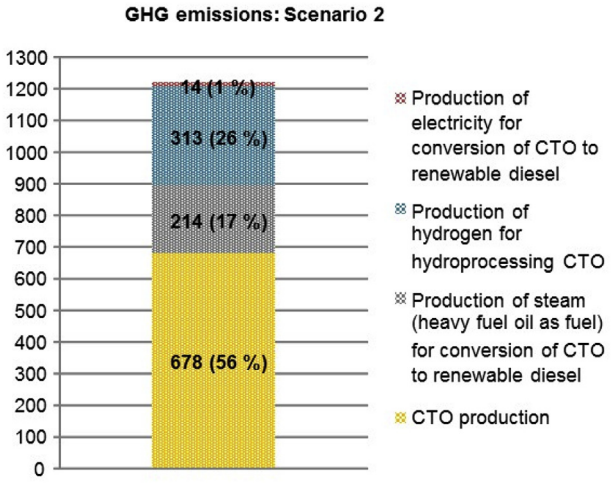

Fig. 7. Balance of GHG emissions assigned to CTO production and processing to renewable diesel.

Table 9
Comparison of GHG emissions in Scenarios 1 and 2.

Process	Scenario 1 GHG (kg product/ Mg CTO)	Scenario 2 GHG (kg product/ Mg CTO)
CTO Production	678	678
Electricity demand	41	13
Steam demand	221	214
Hydrogen demand	0	313
Total	**940**	**1218**

production is 56%, the amount attributed to hydrogen production for hydroprocessing is 26%, and the amount linked to steam generation for renewable diesel production is 17%.

Like in Scenario 1, the amount of TOP that is produced (370 kg/t CTO) is sufficient to replace all the heavy oil needed to generate steam for the process. Therefore, substracting the amount of emissions attributed to steam generation reduces the total emissions to 1004 kg CO_2-eq./Mg CTO.

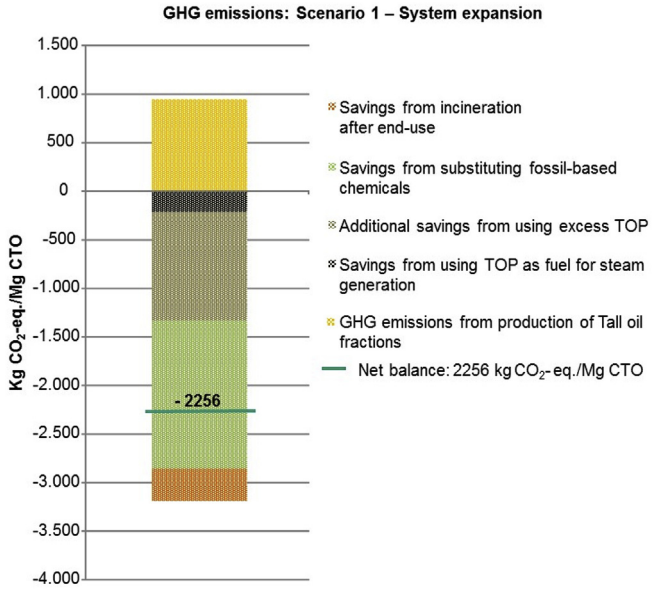

Fig. 6. Balance of GHG emissions for the expanded system in Scenario 1.

Fig. 8 shows the balance of GHG emissions taking into account the expanded system.

Combustion of TOP instead of heavy oil may replace a total amount of 1338 kg CO_2-eq./Mg CTO. Combustion of renewable diesel instead of fossil diesel allows a savings of 1998 kg CO_2-eq./Mg CTO. Therefore, net balance gives an amount of saved greenhouse gas emissions of 2118 kg CO_2-eq./Mg CTO.

3.4. Comparison of impact on global warming

In comparison, the LCA shows that the amount of GHG emissions generated from the use of 1 Mg of CTO to produce biochemicals (Scenario 1) is about 1.3 times less than the GHG emitted when it is used for the production of renewable diesel (Scenario 2). The key process contributing to the global warming impact in Scenario 2 was the use of hydrogen to hydroprocess CTO. Traditonally, hydrogen is produced from natural gas through steam reforming, which amounts to high GHG emissons. In both scenarios, the TOP fraction was modelled to substitute heavy oil for the production of steam thus saving potential emissions.

When considering the expanded system, the values show an

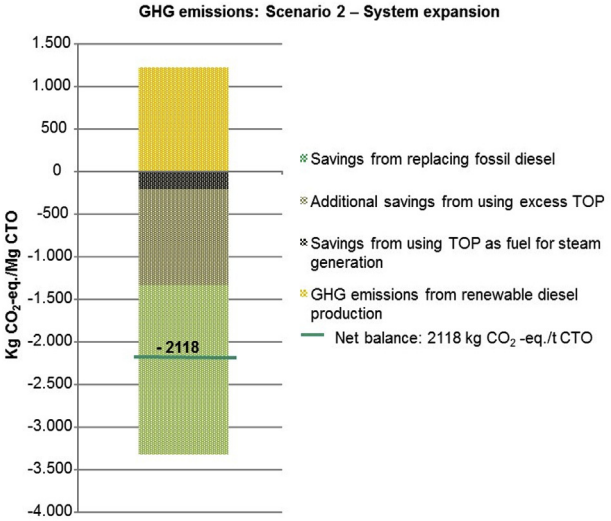

Fig. 8. Balance of GHG emissions for the expanded system in Scenario 2.

Table 10
Job impact assessment – terminology and standard definitions (Rockström et al., 2009).

Terminology	Standard definition
Direct Jobs	The total number of associated primary jobs generated within the industry
Indirect Jobs	The number of jobs generated as a result of inter-industry transactions as a result of heightened demands in the primary industry
Induced Jobs	The number of new jobs generated per million euros of output value (revenues) resulting from the economic activity in the primary industry

overall savings of the same order of magnitude (−2256 kg CO_2-eq./t CTO for Scenario 1 and -2118 kg CO_2-eq./t CTO for Case Scenario 2).

For the expanded system in both scenarios, the balance of GHG emissions is dependent on the savings potential of respective fossil-based substituted products. Furthermore, when considering the end-of-life, it was assumed that a large part of bio-chemicals produced from CTO can be incinerated at the end of their lifecycle. There is however uncertainty in this assumption as some products may be disposed in landfills, while others may be recycled. Nonetheless, one key difference between both scenarios is that, typically chemicals have a longer use-life than fuels before they end up in the environment.

In this LCA it was assumed that any biogenic CO_2 emitted by burning renewable diesel is not accounted, since the emitted carbon was captured by the biomass before. However, resorption of CO_2 by forest regrowth takes several decades (Agostini et al., 2013), considering the annual global CO_2 uptake by forest regrowth is 0.9 ± 0.6 Gt C/yr (IPCC, 2007b), and it varies throughout the life cycle of a forest stand (Kolari et al., 2004). Therefore, the release of greenhouse gases occur at a faster rate if CTO is used to produce renewable diesel (although it is produced from biogenic sources) instead of bio-chemicals.

In conclusion, using CTO as a raw material can contribute to mitigating climate change in two ways: (a) by replacing non-renewable materials and energy, and (b) by storing carbon for a longer time in the form of products until the end of their useful life. Because chemical products derived from crude tall oil usually have a longer useful lifetime than renewable diesel, the release of greenhouse gases from biomass burning is expected to occur at a faster rate if crude tall oil is used to produce renewable diesel instead of chemicals.

4. Economic and social assessment

Besides the environmental assessment, economic and social impact asssessment were conducted to estimate the comparative economic and social added value generated from the utilisation of CTO in both scenarios.

4.1. Goal and scope

For Scenario 1, the economic added value (EAV) was calculated based on the utilisation of CTO in the production of nine selected product applications (see Table 11). Therefore, the EAV assessed the value generated by the CTO fractionators (primary industry) as well as the downstream value generated from processing CTO fractions (DTO, TOFA, TOR and TOP) into each product application. The calculation of the EAV in Scenario 1 was limited to the inter-industry B2B (business-to-business) trading. For Scenario 2, the EAV was calculated based on the revenues generated from the utlisatisation of CTO for renewable diesel. All estimations were based on the premise that 650,000 tonnes of CTO is processed in the EU each year, and the revenues were adjusted to the base year 2016.

Fig. 9 shows the scope of economic assessment as well as the relationship between fractionators revenue and the total EAV along the CTO value chain.

The estimation of job impacts for Scenario 1 includes both the upstream jobs from CTO fractionation and refining, as well as the downstream jobs associated with the CTO based bio-chemicals production. For the renewable diesel case (Scenario 2), it was assumed that no downstream jobs are generated by the economic activity. The rationale being, unlike bio-chemicals, the product chain ends with the production of renewable diesel.

4.1.1. Economic added value estimation

The calculation of the EAV was based on market volumes and market prices for each of the nine selected CTO applications. These values were then aggregated within each step of the value chain as well as for each product within the selected applications to calculate the total added value from the production of bio-chemicals. Fig. 10 shows the context between added value, revenues and costs. The EAV for the production of bio-chemicals from the CTO fractions was calculated using the following equation:

$$\boldsymbol{EAV = [wt\%_i * p_i - wt\%_i * RMC] * CTO\ processed/year}$$

Wherein *wt.%*, is the weight percentage of the corresponding tall oil fraction, *p* is the sales price of the product and *RMC*, the raw material cost. Additionally, by summing up the added values derived from all raw materials from a specific stakeholder of the CTO value chain (e.g. a CTO fractionator or a CTO product upgrading company), the total share of this stakeholder within the value chain can be calculated. As depicted in Fig. 10 the outcome (sales price) from one stakeholder is the input (cost price) for the subsequent

Table 11
Total number of downstream jobs generated by the 'downstream' pine chemical industry.

Product Application	Absolute CTO fractions	Proportional EU Employment
Fuel Additives	18.7	80
Lubricants	5.8	340
Alkyds/Coatings	20.7	1400
Mining Chemicals	0.4	20
Oilfield Chemicals	3.0	180
Paper Sizing Chemicals	2.0	270
Adhesives	19.5	970
Printing Inks	5.5	200
Rubber	5.2	710
Other Major Applications	19.2	950
Total number of downstream jobs		**5120**

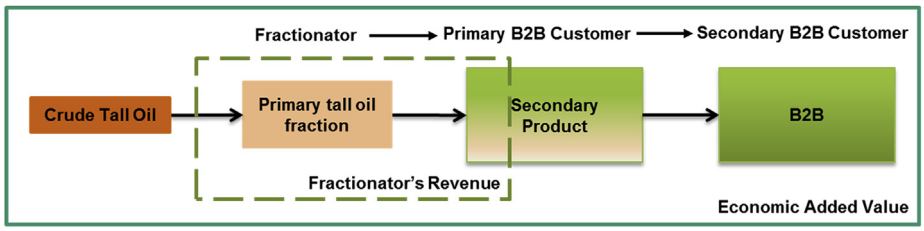

Fig. 9. Relationship between fractionator's revenue and EAV along the CTO value chain.

stakeholder within the value chain.

For the estimation of EAV generated from the conversion of CTO to renewable diesel, it was assumed that 100% or 650,000 tonnes of CTO is converted into renewable diesel per year in Europe. The total added value was therefore the revenue generated from the final sale of renewable diesel in the European market.

4.1.2. Social impact estimation

This social impact assessment aims to estimate the total number of jobs generated by the existing pine chemicals industry in Europe, as well as the potential number of jobs that could be generated if all the EU wide available CTO were diverted to the production of renewable diesel.

The assessment takes a mixed methodology approach combining survey data along with input-output (I/O) tables and social accounting matrices to estimate the total generated employment. The total generated employment is an aggregation of direct jobs, indirect jobs and induced jobs. The inventories and survey from primary data sources were used to estimate the generated 'Direct jobs' for both scenarios. The I/O analysis in the form of multipliers based on the resultant sectoral rise in demand and output were used to estimate the generated 'Indirect jobs'. These multipliers were verified with industry specific multiplier from CEFIC (Hadhri, 2017) and EU wide multiplier based on industrial output from Eurostat, (2016).

Additionally, as with EAV, for Scenario 1, the jobs generated in the downstream markets were further estimated. Those were calculated with the help of the proportional volumes of CTO intermediates used in final products. The absolute share of CTO fraction in corresponding application product groups is depicted in Table 11 (Aryan et al., 2016). In Scenario 2, the jobs generated within the biofuel industry were derived from employment data in reports and company statistics of CTO-based biodiesel producers as well as manufacturers producing similar products. Table 10 illustrate the various types of employment effects investigated in this study.

4.2. Results and discussion – economic impact assessment

4.2.1. Economic added value from scenario 1

The EAV generated by Scenario 1 was calculated using the formula introduced earlier. Fig. 11 shows the results. It was found that, approximately 660 million euros in added value was generated by the primary industry (CTO fractionators) alone in the European Union in 2016. Wherein, 46% of the revenue was generated from the production and upgrading of TOR, 34% from TOFA, 14% from TOP, and finally, 6% from the production and upgrading of DTO.

In addition, when including the value generated by the downstream industry, the Total Added Value (TAV) of the CTO value chain in Europe was about 1.75 billion Euros in 2016. Wherein, 51% of the TAV was generated from the upgrading of TOR, 38% from TOFA, and 6% from DTO into product intermediates for final application. The range indicator in Fig. 11 shows the fluctuation in the TAV based on the respective composition of individual primary tall oil fractions.

4.2.2. Economic added value from scenario 2

The calculation of the TAV for the production of renewable diesel from CTO was based on the LCA assumptions, namely, yields, process conditions and parameters, as well as products and product distribution (see Fig. 12).

Fig. 12 shows the typical product distribution from hydroprocessing of fatty acids (similar to TOFA) and other bio-based oils to fuels. CFPP (cold filter plugging point) is one of the key parameter for fuels and in specific for diesel fuels. In addition, for the diesel derived jet fuels the corresponding freezing properties determines to a high degree the total economic value of the obtained product mixture. Conventional jet fuel must have a CFPP number of at least -

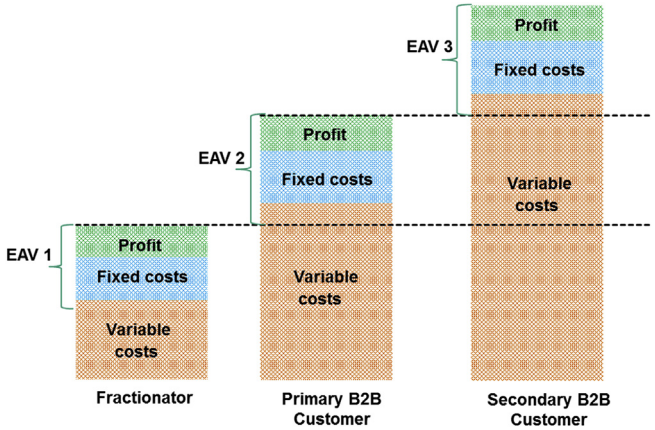

Fig. 10. Relationship between fractionator's revenue and EAV along the CTO value chain.

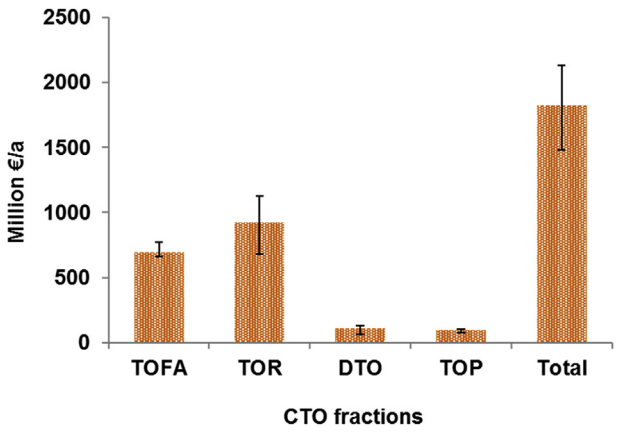

Fig. 11. Calculated total added value (TAV) of the EU pine chemicals industry.

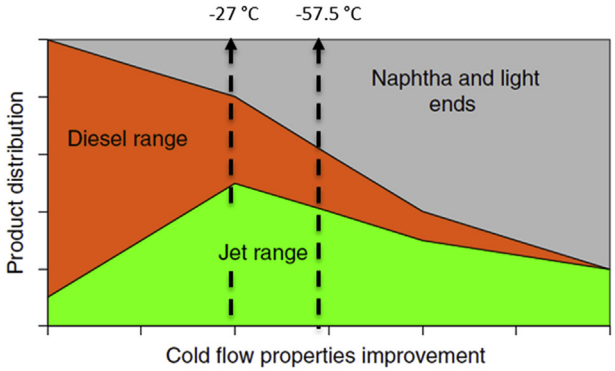

Fig. 12. Product distribution from hydroprocessing of fatty acids, vegetable oils and animal fats depending on cold flow properties of the fuel fraction, modified from (Starck et al., 2016).

47 °C to fulfil the requirements for Jet-A1 (Starck et al., 2016). When linear molecules like fatty acids are hydrotreated, the products are linear molecules that do not fulfil the cold flow requirement and are solids at room temperature. In order to improve cold flow properties, a certain amount of branching is necessary. This is done by hydroprocessing, which is always accompanied by some yield losses. As illustrated in Fig. 12, the conversion of plant oil fractions like CTO to renewable diesel has relative trade-offs in yield between diesel, naptha and diesel derived jet fuel.

Fig. 13 shows the comparison of the TAV calculation and the added value from Scenario 1 with the added value generated from the hypothetical production of renewable diesel in Scenario 2. The upper quartile range (see green range indicator) is added value that includes subsidies that companies producing renewable diesel receive, while the lower quartile range refers to the spot pricing value used for the TAV calculation. The average spot price for diesel in 2016 was 480 €/t (IndexMundi, 2016). The TAV generated by Scenario 2 excluding green premium was estimated at 300 million euros in 2016.

In conclusion, the existing value chain of pine chemicals derived from CTO in the EU generated almost 4 times the added value than

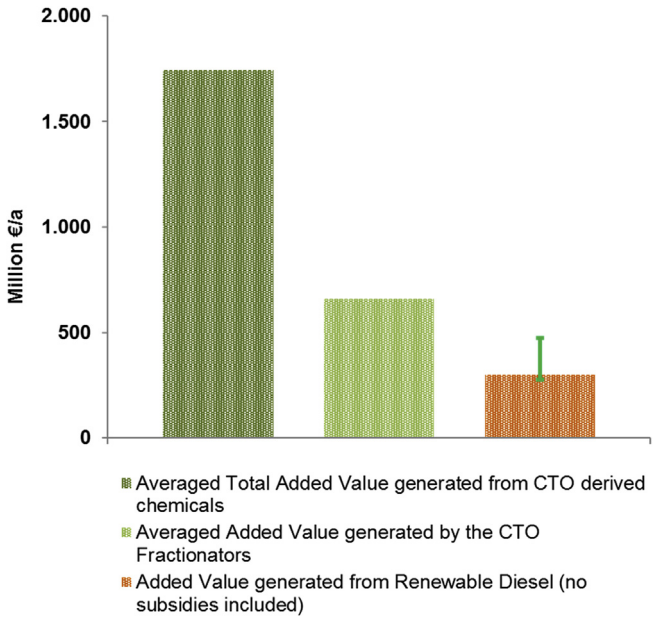

Fig. 13. Comparison of the TAV from the production of bio-chemicals (scenario 1) vs renewable diesel (scenario 2).

the best case scenario considering the conversion of 650,000 of tall oil into renewable diesel in 2016. In accordance with this estimation, the EAV generated from the fractionators selling CTO fractions and performing forms of partial upgrading alone exceeds the EAV generated from those producing renewable diesel by almost 40%, assuming no incentives or tax subsidies are included.

4.3. Results and discussion – job impacts

4.3.1. Job impact of scenario 1 – upstream industry

The total number of jobs generated by the CTO fractionators in Scenario 1 is shown in Fig. 14. Upstream CTO bio-refineries are spread across the geographical length of EU where some of these refineries upgrade CTO fractions into value added products that are subsequently sold into specific B2B market applications. As a first step, the number of direct jobs associated to the upstream CTO bio-refineries in the EU was estimated through primary research in forms of surveys and questionnaires.

The next step was to estimate the indirect employment generated from the inter-industry exchange of goods and services with the primary industry (CTO refiners). This was estimated from aggregated sectoral data provided for the EU chemical industry (excluding pharmaceuticals) by CEFIC (Hadhri, 2017). Upon estimating indirect jobs, the final step was to assess the economy wide impact of the EU pine chemicals industry in the form of induced jobs. Economy wide multipliers (Eurostat, 2016) were used to estimate the induced employment effects per million euros of industrial output (revenues) in 2016. It must be noted that the multipliers used to estimate induced employment effects are valid at a particular point in time, where the underlying assumption is that the trading patterns and economic trends are stable.

The estimations show that the primary or the upstream industry processing CTO into intermediates and preliminary products generates about 9900 jobs in total. Of which 1000 jobs are directly attributed to the Tall-oil fractionators, 3000 jobs are generated indirectly as a result in inter-industry exchange of goods and services, and finally an additional 5900 jobs are created due to induced job effects.

4.3.2. Job impact of scenario 1 - downstream industry

The tall-oil intermediates (TOFA, DTO, TOR and TOP) processed by the CTO fractionators and refiners are used by the downstream industry to produce a range of products. The typical percentage by weight of tall-oil fractions ending in selected market applications chosen in this study is shown in Table 11. Unlike upstream jobs, the downstream job estimates were calculated from the proportional volumes of the CTO intermediates ending in respective application sectors. The estimations relied comprehensively on the secondary

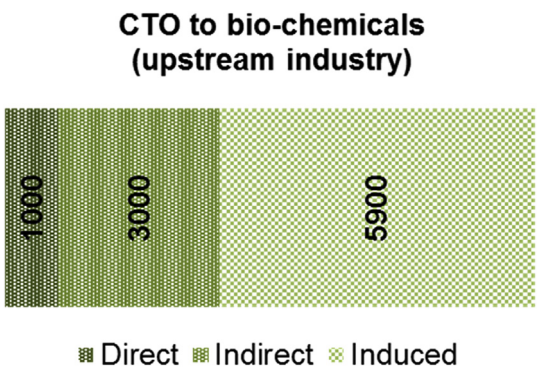

Fig. 14. Total number of direct, indirect and induced jobs generated by the 'upstream' CTO industry (scenario 1).

data from wide range of industrial sector groups (e.g. CEFIC, CEPI, ETRMA, FEICA etc.).

Table 11 shows the estimation of the total number of additional downstream jobs generated by the EU pine chemical industry. The pine chemical industry provides many skilled and semi-skilled jobs along its value chain in engineering, R&D, chemistry, logistics, sales & marketing. In total about 5120 direct jobs were generated in the downstream industry in 2016.

The indirect and induced jobs generated by the CTO downstream industry was out of scope of this study.

4.3.3. Job impact of scenario 2 – total jobs

An estimation of the total number of jobs that could be generated when 650,000 tonnes of the CTO available in Europe is converted to the production of renewable diesel is shown in Fig. 15. The first step was to estimate the number of direct jobs associated with the production of renewable diesel. The direct jobs generated in Scenario 2 was estimated taking into account the publicly available employment numbers from the leading fats and oils processing biofuel producers in Europe. For e.g. NESTE Oil can convert up to million tonnes of used cooking oil (UCO) and employs about 250 people (Neste Oil, 2014). As with Scenario 1, the next step was to estimate the indirect employment resulting from the inter-industry exchange of goods and services with primary biofuel producers. This was estimated by the aggregated sectoral data provided by CEFIC (Hadhri, 2017). Finally, the induced employment effects were calculated as the number of jobs created per million euros of revenues generated.

As outlined earlier, the production of renewable diesel generated a total added value of 300 Million euros (excluding green premium) in 2016. According to that estimation, the process route involving the conversion of CTO into renewable diesel would generate only 2800 jobs in total. Of which, only 100 jobs were direct jobs, while 300 jobs were generated indirectly as a result in inter-industry exchange of goods and services, and finally an additional 2400 jobs were created due to induced job effects Furthermore, as explained in earlier section, the renewable diesel route does not generate any downstream jobs.

In conclusion, when conducting a cost-benefit analysis, the undesirable impact of diverting this limited feedstock from its historic utilisation in the pine chemicals industry to its rising application for the production of biofuels became even more prominent. The total European consumption of fuels in 2016 amounted to 296 Mtoe (million tonnes oil equivalent). The total biofuels share in Europe for the same time period was approximately 14.4 Mtoe (EurObser'ER, 2017), of which, the biodiesel share amounted to 11.2 Mtoe. If all available amounts of CTO in the EU (650, 000 tonnes) were to be converted into renewable diesel, this would contribute a mere additional 0.2% to the entire European transportation fuel consumption. On the other hand, diverting CTO from the established pine chemicals industry could have a substantial economic and social impact. Hence, from a socioeconomic standpoint, the utilisation of CTO for chemicals presents a better option.

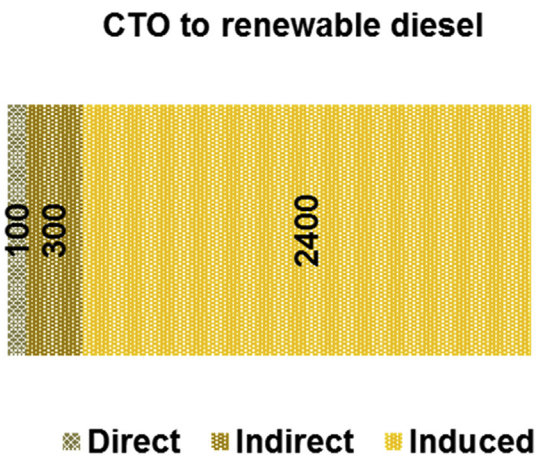

Fig. 15. Total number of direct, indirect and induced jobs generated in Scenario 1.

5. Conclusion

Crude tall oil is an important but scarce resource that can be utilised in two distinct pathways. Through cascading principle, CTO can be processed into key fractions for the production of a multitude of bio-chemicals as done by the pine chemical industry for decades. However, in the recent years, there is a competing interest in utilising CTO to produce biofuels. Hence, an integrated assessment was conducted to holistically weigh the environmental, economic and social impacts of the potential diversion of CTO from its historic utilisation in bio-chemicals towards the new CTO-based renewable diesel application.

This study has revealed that, from an environmental, economic, and social standpoint, the cascading use of CTO for bio-chemicals has lower impacts on global warming and higher socioeconomic added value compared to the production of renewable diesel. CTO-based chemicals demonstrate a broad range of applications and allow a diverse value chain implemented throughout many industries. In addition, CTO-based chemicals demonstrate a good alternative for conventional fossil-based alternatives that have higher carbon footprints.

In specific, the impact on global warming associated to CTO-based chemicals was 940 kg CO_2-eq./Mg CTO. This is relatively lower compared to 1218 kg CO_2 eq./Mg CTO associated with renewable diesel derived from CTO. Furthermore, when considering the expanded system to estimate the savings potential, showed a similar trend (2256 kg CO_2-eq./Mg CTO for bio-chemicals and 2118 kg CO_2-eq./Mg CTO for renewable diesel).

The economic added value assessment demonstrated a clear benefit for bio-chemicals production compared to renewable diesel from CTO. Wherein, the total added value generated along the CTO value from bio-chemicals was around 1.75 billion Euros, the renewable diesel route generated a value add of 475 million Euros in 2016 (this value includes the green premium received for biodiesel production). It is to be noted that the value chain considered in this study for bio-chemicals is restricted to business to business (B2B) transactions, therefore an even higher economic added value can be expected when business to customer (B2C) is considered.

Finally, the social impact assessment showed that the pine chemicals industry generated around 4000 direct and indirect jobs from CTO fractionation and upgrading alone. A further 5120 direct jobs were estimated to be generated by the downstream industry converting tall oil intermediates to consumer products. In comparison, the production of renewable diesel from CTO generated only 400 direct and indirect jobs.

In summary, the limited global availability of CTO as a raw material makes its simultaneous utilisation for material and energetic applications less feasible. Despite considering a 100% utilisation of EU wide available CTO for renewable diesel production, the overall impact of energetic (in biofuels) use was many folds lower than the material use (as biochemicals). Therefore, there is no environmental or socioeconomic advantage from the diversion of CTO from its current cascading use in the European pine chemicals industry to produce biofuels.

The integrated approach presented in this paper allows for comparison of economic, social and environmental impacts emerging from the competing use of raw material. Besides assessing smart and sustainable use of raw materials, it also helps as a decision-making tool for assessing the impact of future legislative changes on similar bio-based feedstock with multiple competing uses and markets like rapeseed oil, tallow fats, used cooking and coffee oil that are used for food, feed, chemicals and biofuels.

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Disclosure

The authors declare that they have no conflict of interest.

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